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MEMORANDUM REPORT ARBRL-MR-02896

(Supersedes IMR No. 452)

THE DEVELOPMENT OF AN INTERIOR BALLISTIC MODEL FOR AUTOMATED CONTINUOUS PROPELLANT PRODUCTION CONTROL

Paul G. Baer
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January 1979



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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| mjp/jmk As a part of Project CASBL (Continuous Automatic Single Base Propellant Line), two gun interior ballistic computation methods were evaluated for the purpose of replacing charge establishment gun firings with predictions from a model. Such predictions in a continuous propellant production plant would eliminate the delay encountered when propellant acceptance tests are conducted at a proving ground. A differential coefficient method and an interior ballistic method based on ballistic similitude were used to predict the performance of a large number of 155-mm and 175- | | |

mm propellant production lots and a few experimental lots for both guns whose chemical and physical properties spanned the extreme ranges of variability to be expected during production.

Of the two methods, the differential coefficient method gave the better results. In general, the standard deviation of error values for muzzle velocity using the differential coefficient method is about one half that of the ballistic similitude method. While the differential coefficient method gave the better results, this approach has the serious drawback of being applicable only if experimental firings have been conducted with propellant lots whose ballistic properties span the complete ranges of properties expected during production.

The effect of closed chamber measurement errors on predicted muzzle velocities was determined. Standard deviation errors in relative quickness and relative force produced errors in the prediction of muzzle velocity ranging from 0.38 percent to 1.10 percent of the muzzle velocity. It appears from these results that reduction in muzzle velocity prediction error requires reduction in closed chamber measurement error.

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INTRODUCTION

The first Continuous Automatic Single Base Propellant production Line (Project CASBL) will go on stream at Radford Army Ammunition Plant. One of the critical problems which must be solved to provide for the operation of this propellant production line is the development of a rapid and accurate method of charge weight estimation to allow on-line loading of gun charge packages without the delays encountered in using proving ground gun firings to establish propellant charge.

An on-line gun interior ballistic computer model has been proposed to replace the gun in the charge establishment role. The placement of such a model in a continuous propellant manufacturing plant is illustrated in Figure 1. Figure 1 is a flow diagram showing the relationships between the propellant line, the propellant line process controller, and the interior ballistic model. Raw material goes in at the top of the line; the fabricated propellant grains come out the bottom, are packed into gun charges, and sent to storage. Samples of the production are taken off at various parts of the line, subjected to chemical and physical tests, and the information from these tests is sent to a process controller which in turn controls the operation of the machines on the line in order to produce a product of acceptable quality. Prior to charge packing, propellant samples are fired in the closed chamber. Information from the closed chamber tests and from the chemical and physical tests go to the gun interior ballistic model; information from the gun model then goes to the process controller and the charge packing station.

Functional details of the gun model are illustrated in Figure 2. Propellant chemical composition data from chemical analysis will be processed by a gun thermodynamic model such as the BLAKE code¹ to produce propellant thermodynamic data for use by the gun simulation model. Propellant combustion characteristics and energy data will be provided to the gun simulation model by the closed chamber data reduction program. Physical examination of the propellant will provide the gun model with propellant density and grain dimensions. Gun dimensional data and projectile weight will also be provided to the gun model. The gun simulation model, in turn, will provide muzzle velocity, maximum breech pressure, and other interior ballistic trajectory data. These gun performance data will then be compared with the propellant acceptance criteria and a decision made to accept or reject the propellant lot. If the propellant lot is rejected, this information is sent to the process controller for appropriate action. If the propellant lot is accepted, a charge weight will be computed and this information sent to the process controller.

¹ Eli Freedman, "A Brief Users Guide for the BLAKE Program," Ballistic Research Laboratories Interim Memorandum Report 249, July 1974. (Interim report no longer available)

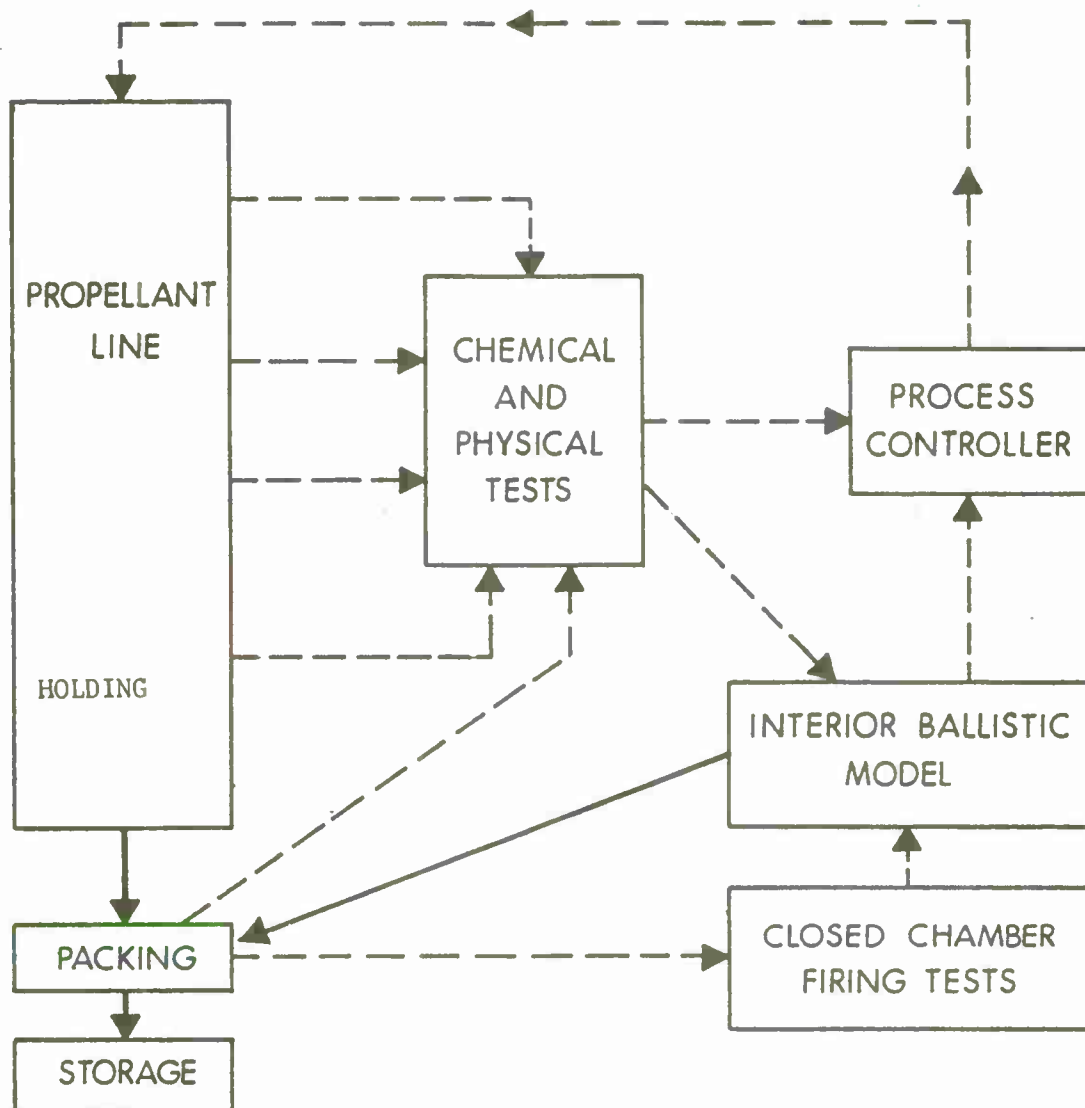


Fig. 1. Flow Diagram for Continuous Propellant Manufacturing Plant

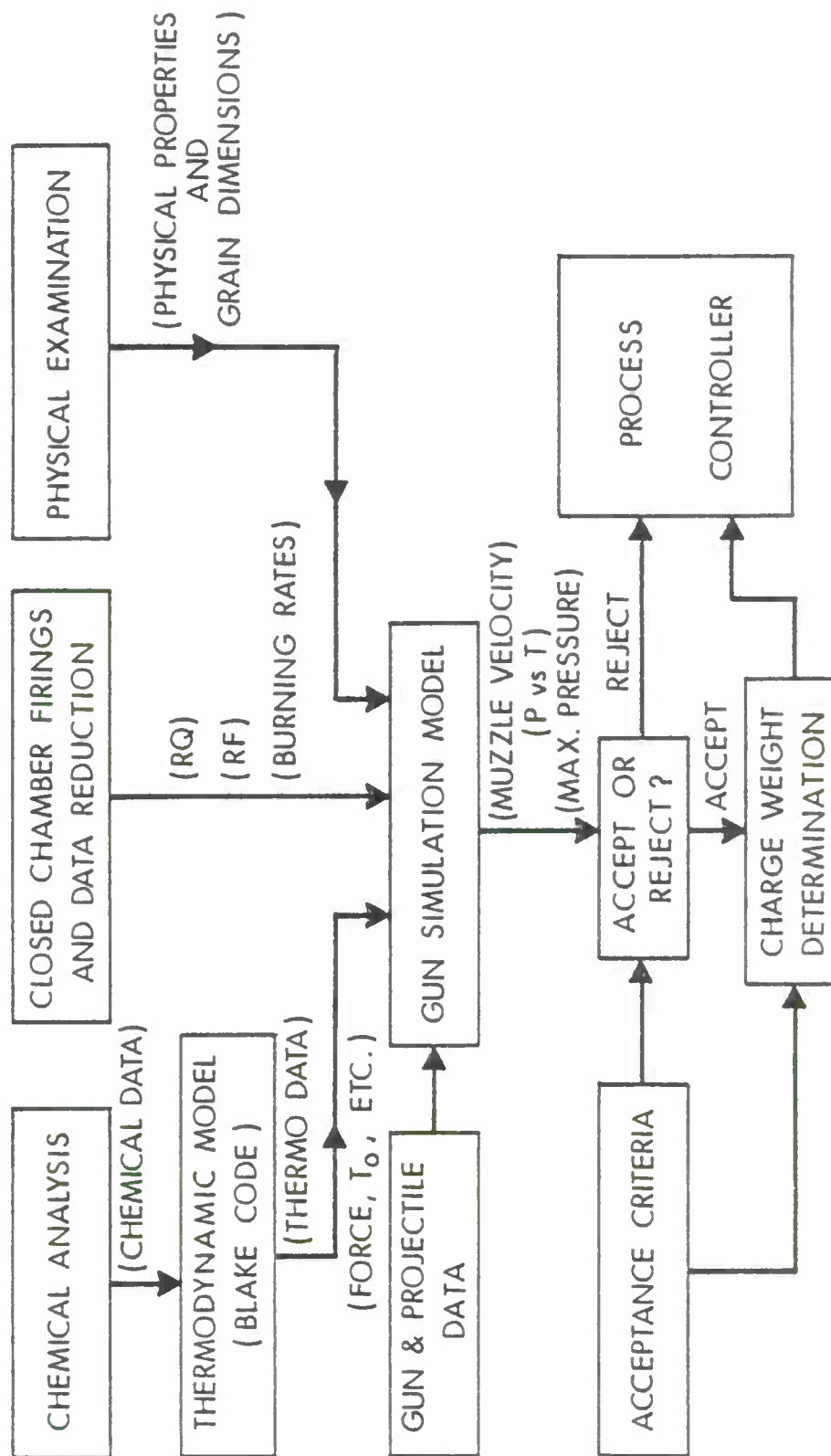


Fig. 2. Flow Diagram, Interior Ballistic Model for Continuous Propellant Testing

The ballistic acceptance plans for the 155-mm howitzer and for the 175-mm gun charges are given in Tables I and II. For the 175-mm gun, this information was obtained from Reference 2 and for the 155-mm howitzer, from Reference 3. It will be noted that the maximum standard deviation in muzzle velocity mentioned in these tables is the round-to-round standard deviation produced by measurement errors, variations in projectile and gun dimensions, and variations in the loaded charges.

Table I. Ballistic Acceptance Plan for
175-mm Gun Propellant Charge, M86A2

Sample - 5 rounds @ 70°F (21°C)
5 rounds @ 140°F (60°C)

70°F (21°C)

Velocity Limits: 2940-3060 f/s (896-933 m/s)
Maximum Standard Deviation: 10 f/s (3 m/s) 0.33%
3 σ : 30 f/s (9 m/s) 0.99%

140°F (60°C)

Velocity Limits: 3015-3130 f/s (919-954 m/s)
Maximum Standard Deviation: 16 f/s (5 m/s)
Maximum Zone 3 Pressure: 48,400 psi (334 MPa)
Maximum Excess Charge Pressure: 58,000 psi (400 MPa)

Table II. Ballistic Acceptance Plan for
155-mm Howitzer Propellant Charge, M4A2

Sample - 5 rounds @ 70°F (21°C)
5 rounds @ 140°F (60°C)

Velocity Limits: 1825-1875 f/s (556-572 m/s)
Maximum Standard Deviation: 9.2 f/s (2.8 m/s) 0.50%
3 σ : 27.6 f/s (8.4 m/s) 1.50%

Permissible Individual Pressure @ 70°F (21°C): 40,500 psi (279 MPa)
Permissible Individual Pressure @ 140°F (60°C): 44,100 psi (304 MPa)

² Fred J. Fitzsimmons, "Concept of Scope of Work for PEMA Project 5774186 Acceptance of Propellant Via the Continuous Process (PROJECT AUTOCAP)," Product Assurance Directorate, Picatinny Arsenal Report No. SMUPA-QA-A-P-55-73, December 1972.

³ "Proving Ground Acceptance Test Procedure for Artillery Propellants, Charge, Propelling, 155-mm M4A2," Aberdeen Proving Ground Supplement P-155H-7J,C1, 13 January 1975 and 5 August 1974.

DESCRIPTION OF INTERIOR BALLISTIC METHODS

Two interior ballistic methods were used in this study: the differential coefficient method and the ballistic similitude method. In the differential coefficient method, the muzzle velocity and the maximum breech pressure are predicted by two equations:

$$\begin{aligned} \frac{\Delta V}{V} = & a_1 + b_1 \frac{\Delta RQ}{RQ} + c_1 \left(\frac{\Delta RQ}{RQ} \right)^2 + d_1 \frac{\Delta RF}{RF} \\ & + e_1 \left(\frac{\Delta RF}{RF} \right)^2 + f_1 \frac{\Delta CW}{CW} + g_1 \left(\frac{\Delta CW}{CW} \right)^2 \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{\Delta P}{P} = & a_2 + b_2 \frac{\Delta RQ}{RQ} + c_2 \left(\frac{\Delta RQ}{RQ} \right)^2 + d_2 \frac{\Delta RF}{RF} \\ & + e_2 \left(\frac{\Delta RF}{RF} \right)^2 + f_2 \frac{\Delta CW}{CW} + g_2 \left(\frac{\Delta CW}{CW} \right)^2 \end{aligned} \quad (2)$$

where: ΔV = predicted muzzle velocity minus standard muzzle velocity
 V = standard muzzle velocity
 ΔRQ = experimental relative quickness minus standard relative quickness
 RQ = standard relative quickness
 ΔRF = experimental relative force minus standard relative force
 RF = standard relative force
 CW = standard propellant charge weight
 ΔCW = experimental propellant charge weight minus standard propellant charge weight
 ΔP = predicted maximum breech pressure minus standard maximum breech pressure
 P = standard maximum breech pressure
 a_1, a_2 = constant terms
 b_1, b_2, etc = differential coefficients

For small perturbations in relative quickness, relative force and charge weight, the constant and second order terms should disappear. In fact, good estimates for these differential sensitivity coefficients may be made from a perturbation analysis of either the ideal gun energy conservation equation or from a suitably more complex interior ballistic

model. In practice, more accurate results are usually obtained from an empirical correlation of the experimental data. Higher order terms in Equations 1 and 2 are justified for those cases where the perturbations are no longer small.

The differential coefficient method has been used previously for charge assessment. Results of the application of the method have been reported by Jackson⁴ and by Auerbach⁵.

The ballistic similitude method was originally developed by Bennett⁶ in 1921 for the purpose of constructing gun interior ballistic tables. Since in those precomputer days all differential equations had to be integrated by hand, simplification of the governing equations was essential. In this method, two unknown parameters (ballistic quickness and velocity factor) are determined by simulation of a known firing and a convenient change of the independent variable in the derived equations makes it possible to evaluate these unknowns independently. Hitchcock⁷ in 1956, integrated the differential equations on a digital computer to generate an extended set of interior ballistic tables to meet the need to deal with modern weapons. In the early 1960's, Frankle revised this method to handle weapons with two propellants (one single-perforated and one seven-perforated grain). It was then programmed for the digital computer so that instead of generating tables, each interior ballistic trajectory problem would be solved as an individual case. Experimental maximum breech pressure and muzzle velocity are needed by the method of compute the ballistic quickness and velocity factor to be used in subsequent new trajectory calculations. The ballistic quickness factor is defined by the following equation:

$$q = \frac{q_1 (CV)^{0.5} (p')^{0.5} (RF)^{\epsilon_1} (RQ')^{\epsilon_2} (1 - Kq(1 - \frac{c}{c_s}))}{WA (1 + e)} \quad (3)$$

⁴ Wendell F. Jackson, "Uniformity of Dupont "NH" Powder for the 155-mm Gun," Dupont Report BL-204-7-6, Burnside Laboratory, November 1939.

⁵ E. Auerbach, "The Use of Closed Bmb Data for Estimating Charge Weights for 105-mm Howitzer," Picatinny Arsenal Report No. 1881, May 1952.

⁶ Albert A. Bennett, "Tables for Interior Ballistics," Ordnance Department Document No. 2039, Washington, DC, April 1921.

⁷ Henry P. Hitchcock, "Tables for Interior Ballistics," Ballistic Research Laboratories Report No. 993, September 1956. (AD #134080) and "Notes on Tables for Interior Ballistics," Ballistic Research Laboratories Technical Note No. 1298, February 1960. (AD #234734)

Where: q = ballistic quickness factor

q_1 = empirical factor determined from a known firing

CV = chamber volume

p' = reduced projectile weight

e = weight ratio

A = bore area

W = propellant web

ϵ_1 = relative force exponent

ϵ_2 = relative quickness exponent

RQ' = web-independent relative quickness after Krier and Shimpi⁸

Kq = q adjustment factor to improve charge weight correction
(after Heppner⁹)

c = propellant weight

c_s = propellant weight used in calibration firing.

The ballistic velocity factor is defined by the following equation:

$$r = r_o \left(\frac{g CV}{p'} \right)^{0.5} (RF)^{0.5} \left(1 - Kr \left(1 - \frac{c}{c_s} \right) \right) \quad (4)$$

Where: r = ballistic velocity factor

r_o = empirical factor determined from a known firing

g = gravitational constant

Kr = r adjustment factor to improve charge weight correction
(after Heppner⁹)

⁸ H. Krier, M. Adams, and S. Shimpi, "Closed Bomb Data Used to Predict Interior Ballistics," University of Illinois Interim Research Memorandum, March 1974.

⁹ Leo D. Heppner, "Final Report of Special Study of an Electronic Computer Program for Interior Ballistics," Test and Evaluation Command Report No. DPS-1711, Aberdeen Proving Ground, Maryland, July 1965.

PROCEDURE FOR THE ASSESSMENT OF THE DIFFERENTIAL COEFFICIENT METHOD

The procedure used to determine the differential coefficients and to assess the method was as follows:

1. Propellant lot acceptance firing data from firings conducted at Aberdeen Proving Ground and Jefferson Proving Ground were obtained and selected portions of these data were stored on magnetic tape cassettes for processing by a small minicomputer.

2. Propellant lot description data were obtained from Radford Army Ammunition Plant. Selected portions of these data were also stored on magnetic tape cassettes.

3. The coefficients for the differential coefficient method, Equations (1) and (2), were obtained from the data for a selected range of propellant lots using a least-squares regression technique. For the least-squares analysis and statistical tests, standard procedures were followed^{10,11}.

4. Once the coefficients were obtained for the equations, the muzzle velocities, maximum breech pressures, and recommended charge weights were computed either for the range of lots used in determining the coefficients or other ranges of lots used in the determination.

5. The differences between the predicted and measured values were computed for each lot. For a range of propellant lots, the values of the average error in prediction, the standard deviation of the error, three times the standard deviation of the error, and the prediction confidence intervals were computed. The prediction confidence interval brackets the predicted value such that one is 99 percent (as computed here) confident that the next observed value will fall within the interval.

Various forms of the differential coefficient equations were used in this study: (1) first order terms with no constant term, (2) first order terms with constant term, (3) first and second order terms with no constant term, and (4) first and second order terms with constant term.

The 155-mm howitzer and 175-mm gun propellant lot ranges used in this study are listed in Table III. In the first column of the table, a symbol designates the range of lots used in the study. The second

¹⁰ "Experimental Statistics - Section 1," Ordnance Engineering Design Handbook, ORDP-20-110, June 1962, Chapters 5 and 6.

¹¹ R. L. Anderson and T. A. Bancroft, "Statistical Theory in Research," McGraw Hill, New York, 1952, Chapter 13.

column designates the gun. The third column designates the range of lots. The fourth column shows the reference lot; the fifth column, the number of lots in a designated lot range; and the sixth column, the number of maximum breech pressure, muzzle velocity data sets used in the analysis. This last number is greater than the number of lots for firings because more than one charge weight per lot was used.

Lot Range C was the experimental set of 175-mm propellant lots whose ballistic properties spanned the range of properties expected during propellant production. These lots were used to predict the performance of the production lots. Results from Lot Range C predictions have been reported previously¹². Also, six lots were picked from Lot Range A such that the relative force and relative quickness values exhibited the same range of values as Lot Range A. This limited set of lots is designated Lot Range AA. The same was done for Lot Range B to produce Lot Range BB. The same was also done for 155-mm Lot Range X to produce Lot Range XX except that only five lots were used. Lot Range SX was a set of experimental 155-mm propellant lots whose ballistic properties spanned the range of properties expected during propellant production. These lots were also used to predict the performance of the production lots.

Selected samples of the better results are listed in Table IV. In this table are listed the correlation lot range, that is, the range of lots for which the set of differential coefficients were calculated; the range of lots for which muzzle velocities, maximum breech pressures, and recommended charge weights were predicted; the gun; and the parameter being predicted. This is followed by the coefficients, the average error, the standard deviation, three times the standard deviation, and the 99-percent confidence interval. The last four items are expressed as percentages of the standard value. Table V gives these standard values for each of the three reference lots used in the study. Plots of the predicted muzzle velocity or maximum breech pressure vs the measured muzzle velocity or maximum breech pressure for some of the differential coefficient predictions are illustrated in Figure 3 through Figure 6 for the 175-mm gun propellant lots and Figure 7 through Figure 10 for the 155-mm howitzer propellant lots. In these figures, the straight line represents the locus of points on which the plotted values would fall if the predicted values were equal to the measured values. The two clusters of points represent data for upper zone charge firings and excess charge weight firings. Also on these plots are illustrated the mean error, the standard deviation of the error, and the differential coefficient equation used to predict the values of either muzzle velocity or maximum breech pressure.

¹² Paul G. Baer, Ingo W. May, and Jerome M. Frankle, "A Comparison of Several Predictive Approaches in Charge Establishment for Large Caliber Artillery Systems," *Proceedings of 11th JANNAF Combustion Meeting, Vol. I, pg. 55-66, Pasadena, California, September 1974.*
CPIA Document No. 281.

Table III. Propellant Data Used in Regression Study

| <u>Symbol</u> | <u>Gun</u> | <u>Propellant Lots</u> | <u>Reference Lot</u> | <u>Number of Lots</u> | <u>Number of P,V, Data Sets</u> |
|---------------|------------|---|--------------------------|-----------------------|---------------------------------|
| A | 175-mm | RAD 65009 to RAD 65574 | BAJ 65312 | 87 | 181 |
| B | 175-mm | RAD 65731 to RAD 67994 | RAD 65306 | 122 | 235 |
| C | 175-mm | RAD A-PEI-441-1 to RAD H-PEI-441-1 | RAD 65306* 67994** | 8 | 16 |
| AA | 175-mm | RAD 65017, 65026, 65029 65215, 65414, 65528 | BAJ 65312 | 6 | 12 |
| BB | 175-mm | RAD 65733, 65736 65982, 65275, 67481 67566 | RAD 65306 | 6 | 12 |
| X | 155-mm | RAD 69337 to RAD 69444 | RAD 68308 | 32 | 96 |
| XX | 155-mm | RAD 69398, 69421, 69422, 69439, 69443 | RAD 68308 | 5 | 15 |
| SX | 155-mm | RAD-PE-441-J to RAD-PE-441-W | RAD 68308 | 15 | 30 |

*Closed chamber reference lot

**Gun firing reference lot

Table IV. Errors in Prediction of Muzzle Velocities, Maximum Breech Pressures, and Recommended Charge Weights for the 155-mm Howitzer and 175-mm Gun Propellant Lots Using the Differential Coefficient Method

| Correlation Range | Predicted Range | Gun | Parameter | a | b | Coefficients | | | e | f | g | Average Error %SV | Standard Deviation, σ %SV | 3 σ %SV | Confidence Interval %SV |
|-------------------|-----------------|--------|-----------|----------|--------|--------------|--------|---------|--------|--------|--------|-------------------|----------------------------------|----------------|-------------------------|
| | | | | | | c | d | | | | | | | | |
| B | B | 175-mm | MV | -0.00145 | 0.285 | -0.367 | 0.228 | 8.199 | 0.671 | 0.536 | 0.000 | 0.296 | 0.889 | 0.773 | |
| B | B | 175-mm | P | -0.0159 | 1.93 | 10.267 | 0.905 | 46.198 | 2.241 | 3.222 | 0.031 | 1.901 | 5.706 | 4.961 | |
| B | B | 175-mm | RCW | 0.00145 | -0.285 | 0.367 | -0.228 | -8.199 | -0.671 | -0.536 | -0.126 | 0.444 | 1.334 | 1.212 | |
| B | A | 175-mm | MV | -0.00145 | 0.285 | -0.367 | 0.228 | 8.199 | 0.671 | 0.536 | 0.056 | 0.522 | 1.566 | 1.439 | |
| B | A | 175-mm | P | -0.0162 | 1.781 | | 1.297 | | 2.443 | | 4.655 | 2.820 | 8.461 | 4.841 | |
| B | A | 175-mm | RCW | 0.00145 | -0.285 | 0.367 | -0.228 | -8.199 | -0.671 | -0.536 | -0.057 | 0.635 | 1.905 | 2.228 | |
| VA | A | 175-mm | MV | -0.00079 | 0.273 | | 0.427 | | 0.672 | | 0.102 | 0.466 | 1.400 | 0.748 | |
| AA | A | 175-mm | P | -0.0456 | 1.670 | | 1.852 | | 2.182 | | 0.816 | 2.693 | 8.081 | 4.484 | |
| AA | A | 175-mm | RCW | 0.00079 | -0.273 | | -0.427 | | -0.672 | | -0.335 | 0.613 | 1.841 | 6.488 | |
| X | X | 155-mm | MV | -0.0010 | 0.150 | 1.298 | 0.305 | 19.800 | 0.424 | 4.770 | 0.000 | 0.312 | 0.937 | 0.846 | |
| X | X | 155-mm | P | 0.0142 | 1.080 | | 2.170 | | 1.876 | | 0.030 | 1.891 | 5.675 | 5.052 | |
| X | X | 155-mm | RCW | 0.0010 | -0.150 | -1.298 | -0.305 | -19.800 | -0.424 | -4.770 | 0.017 | 0.455 | 1.367 | 1.248 | |
| XX | X | 155-mm | MV | 0.0005 | 0.151 | | 0.299 | | 0.665 | | 0.125 | 0.320 | 0.960 | 1.071 | |
| XX | X | 155-mm | P | 0.0229 | 0.956 | | 1.645 | | 1.929 | | 0.917 | 1.909 | 5.728 | 6.480 | |
| SX | SX | 155-mm | MV | 0.0012 | 0.274 | | -0.141 | | 0.730 | | 0.011 | 1.113 | 3.341 | 3.236 | |
| SX | SX | 155-mm | P | 0.0284 | 1.205 | | -2.354 | | 1.435 | | -0.559 | 9.396 | 28.189 | 27.495 | |
| SX | X | 155-mm | MV | | 0.274 | | -0.144 | | 0.727 | | 0.055 | 0.403 | 1.211 | 4.044 | |
| SX | X | 155-mm | P | 0.0284 | 1.205 | | -2.354 | | 1.435 | | -0.009 | 2.562 | 7.688 | 25.101 | |

MV - Muzzle Velocity
P - Maximum Breech Pressure
RCW - Recommended Charge Weight
SV - Standard Value

Table V. Standard Values for 155-mm and 175-mm
Reference Propellant Lots

| Reference Lot No. | Gun | Maximum Pressure | | Muzzle Velocity | | Charge Weight | |
|----------------------|--------|------------------|-------|-----------------|-------|---------------|-------|
| | | psi | MPa | f/s | m/s | lb | kg |
| BAJ 65312 | 175-mm | 51,100 | 352.3 | 3000 | 914.4 | 55.56 | 25.20 |
| RAD 65306 | 175-mm | 47,200 | 325.4 | 3000 | 914.4 | 57.24 | 25.96 |
| RAD 68308 | 155-mm | 36,500 | 251.7 | 1850 | 563.9 | 13.28 | 6.02 |

PROCEDURES FOR THE ASSESSMENT OF THE BALLISTIC
SIMILITUDE METHOD (HITCHCOCK CODE)

The procedures used to determine adjustable parameters for the ballistic similitude method and to assess this method were as follows:

1. The propellant lot acceptance firing data and the propellant lot description data were stored in data files on the UNIVAC 1108 computer's magnetic drum and disc storage.
2. The Hitchcock code was run on the UNIVAC 1108 computer, varying the two empirical factors (q_1 in Equation (3) and r_0 in Equation (4)) in the code until the predicted muzzle velocities and maximum breech pressures agreed with the muzzle velocities and maximum breech pressures obtained from the firings of the reference propellant lots.
3. With the empirical factors held constant, the Hitchcock code was used to predict the muzzle velocities and maximum breech pressures for a range of propellant lots.
4. The differences between the predicted and measured values were obtained for the test propellant lots and then the average error, the standard deviation of the error, and three times the standard deviation of the error were obtained. Confidence limits could not be computed using the values from the Hitchcock code because the method of obtaining confidence limits does not apply to non-linear regression models such as the Hitchcock code.

In Table VI, the errors in predicting muzzle velocities and maximum breech pressures for the 175-mm gun and 155-mm howitzer production lots using the Hitchcock code are listed.

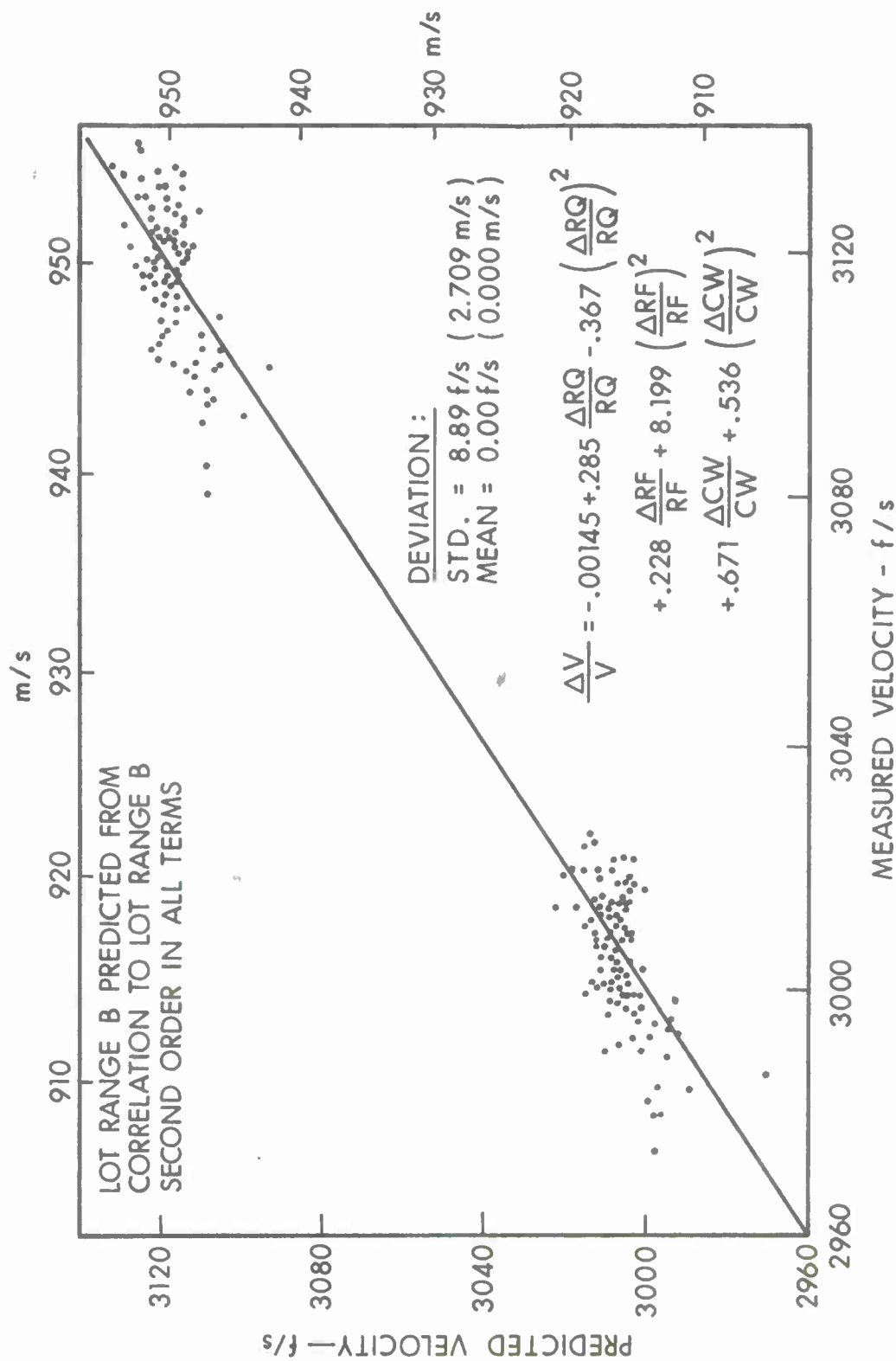


Fig. 3. Prediction of Muzzle Velocities for 175-mm Gun Propellant Lots Using Differential Coefficients. Lot Range B Predicted from Second Order Correlation to Lot Range B

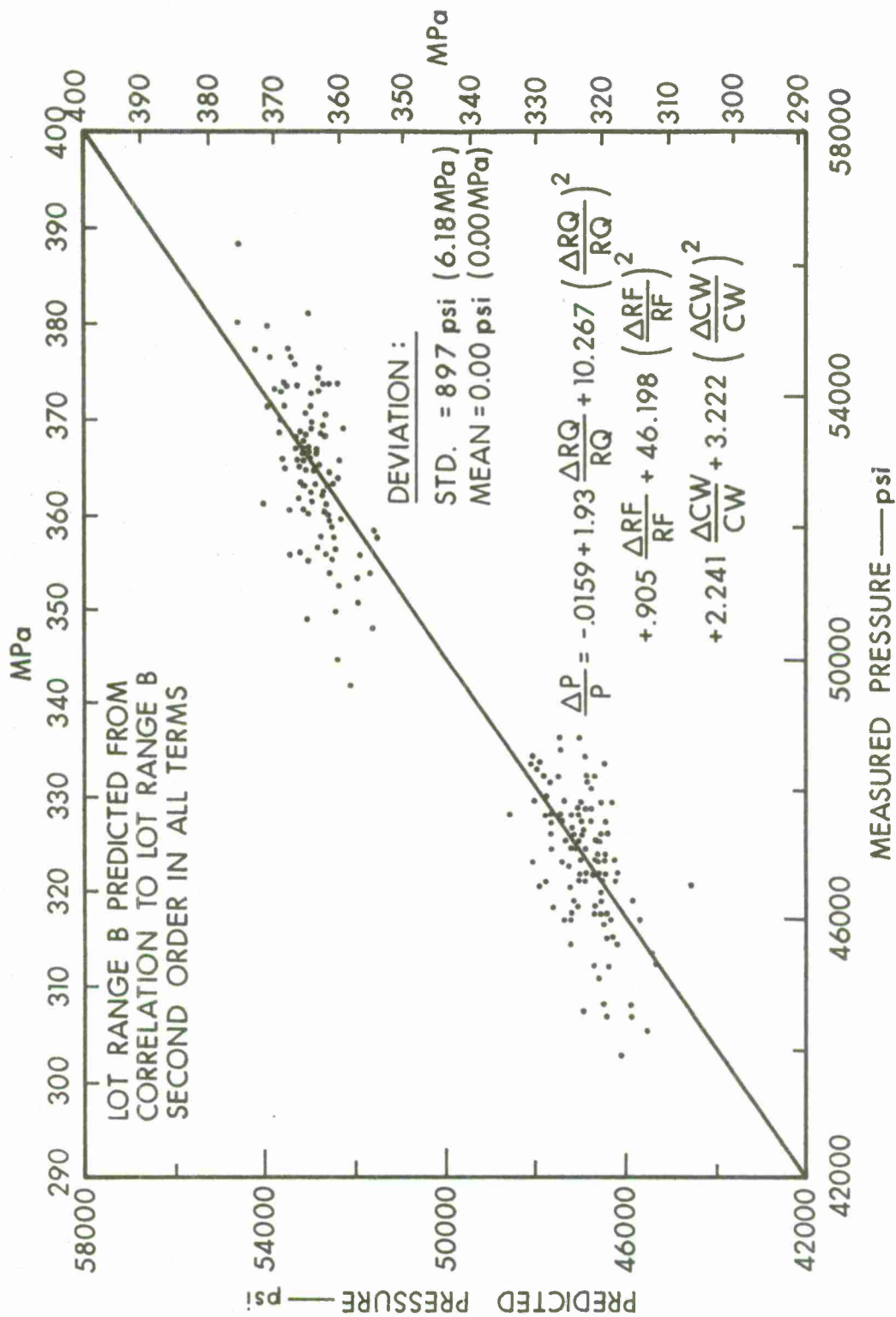


Fig. 4. Prediction of Maximum Breech Pressures for 175-mm Gun Propellant Lots Using Differential Coefficients. Lot Range B Predicted from Second Order Correlation to Lot Range B

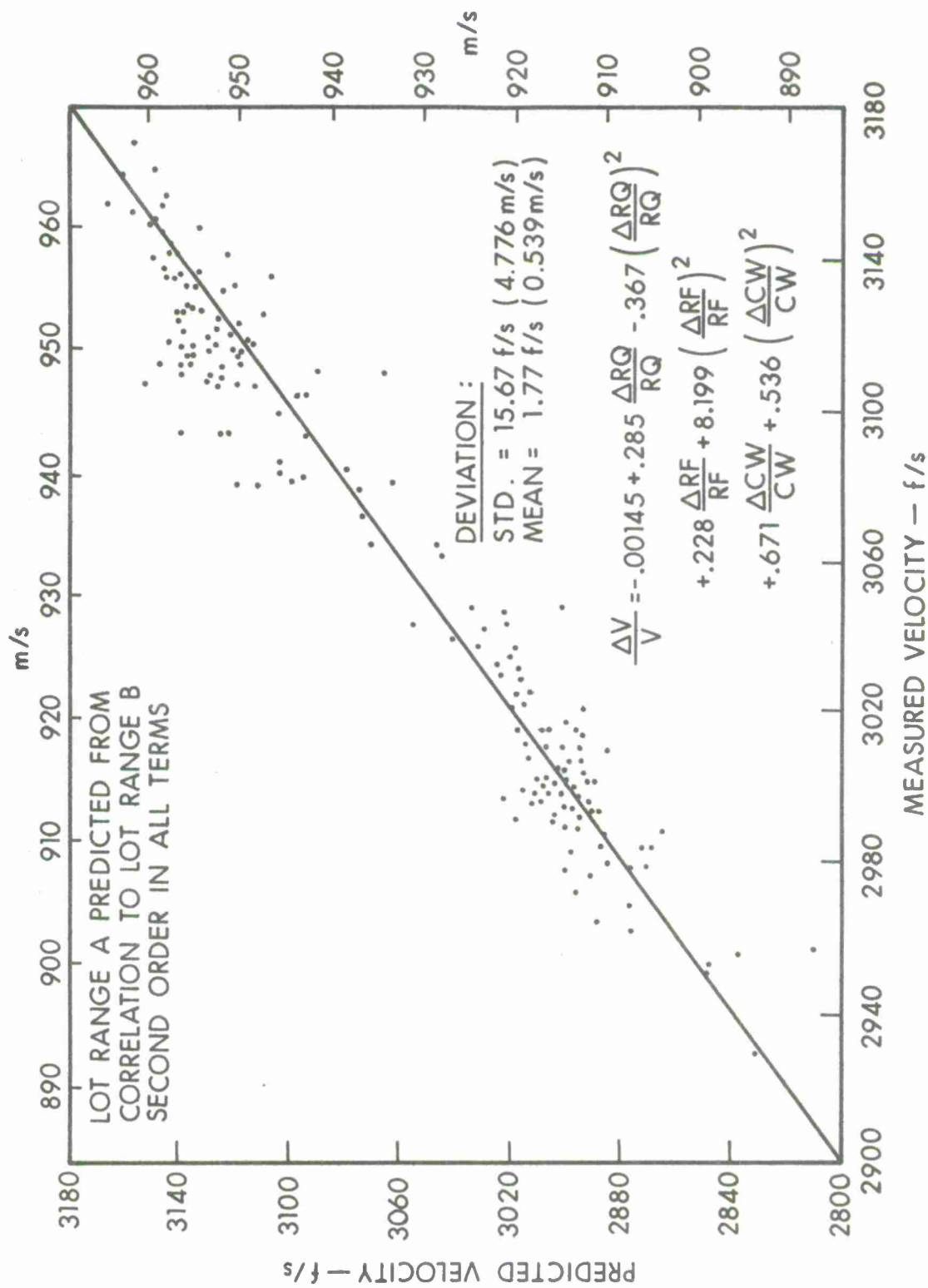


Fig. 5. Prediction of Muzzle Velocities for 175-mm Gun Propellant Lots Using Differential Coefficients. Lot Range A Predicted from Second Order Correlation to Lot Range B

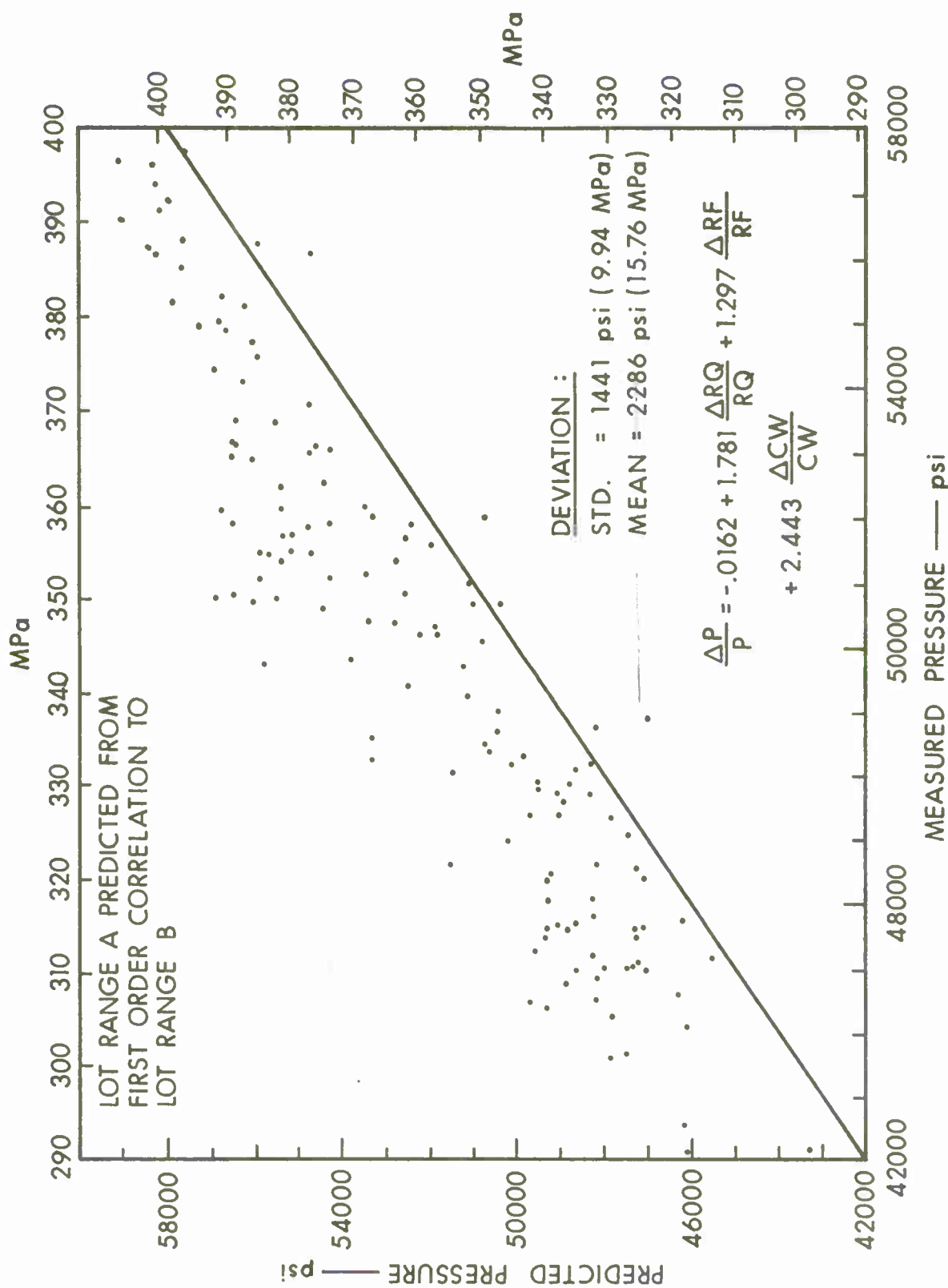


Fig. 6. Prediction of Maximum Breech Pressures for 175-mm Gun Propellant Lots Using Differential Coefficients. Lot Range A Predicted from First Order Correlation to Lot Range B

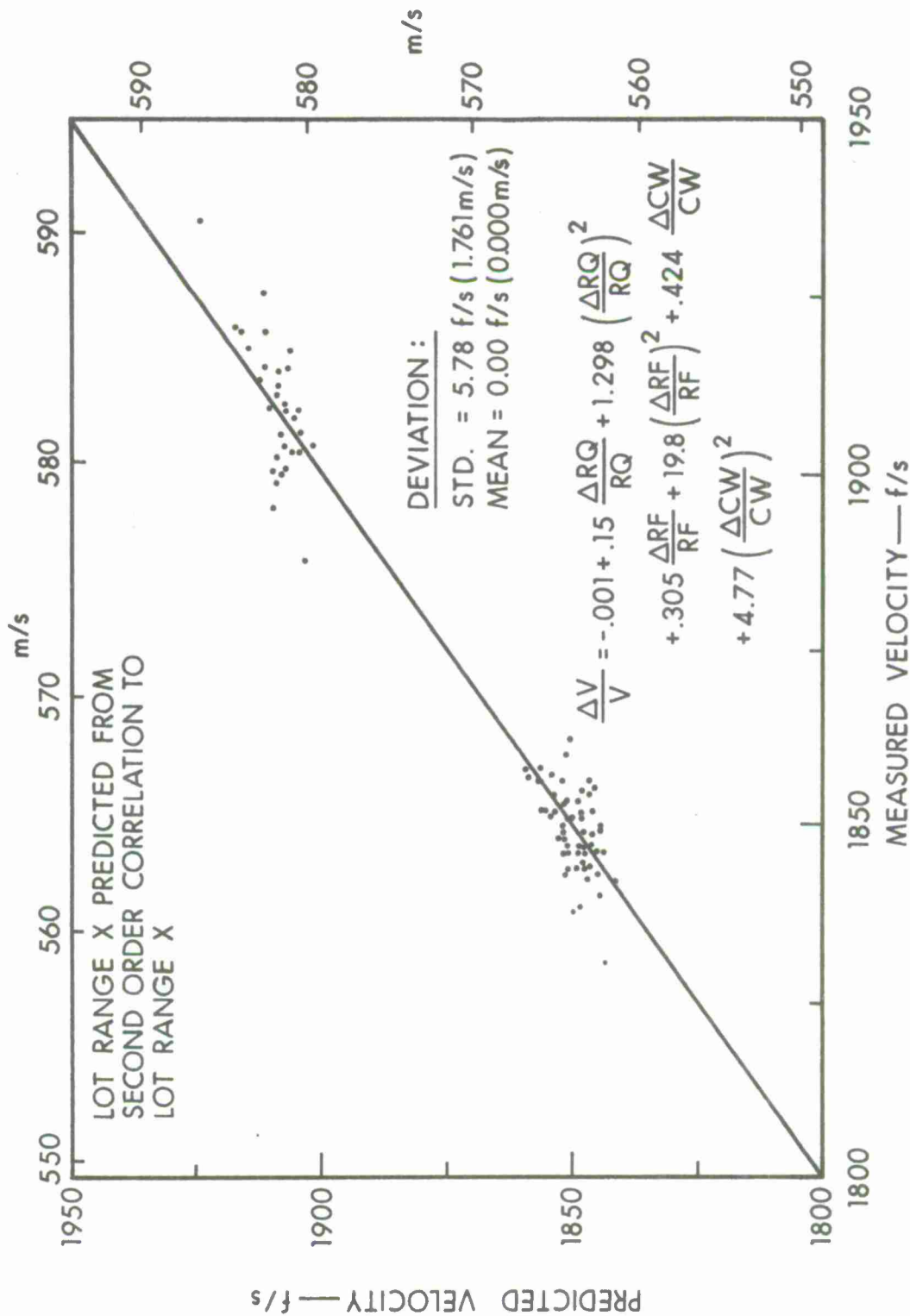


Fig. 7. Prediction of Muzzle Velocities for 155-mm Gun Propellant Lots Using Differential Coefficients. Lot Range X Predicted from Second Order Correlation to Lot Range X

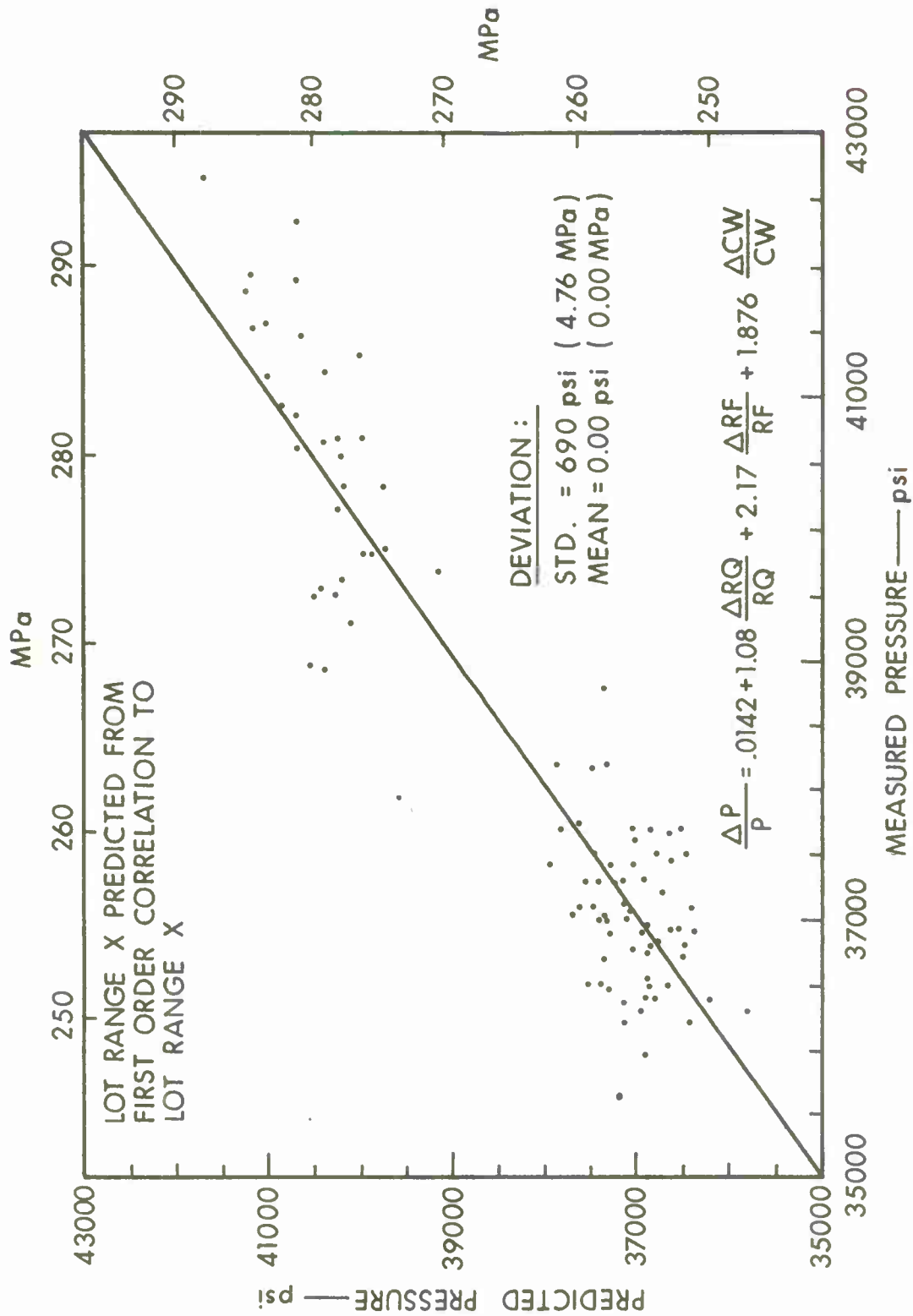


Fig. 8. Prediction of Maximum Breech Pressures for 155-mm Gun Propellant Lots Using Differential Coefficients. Lot Range X Predicted from First Order Correlation to Lot Range X

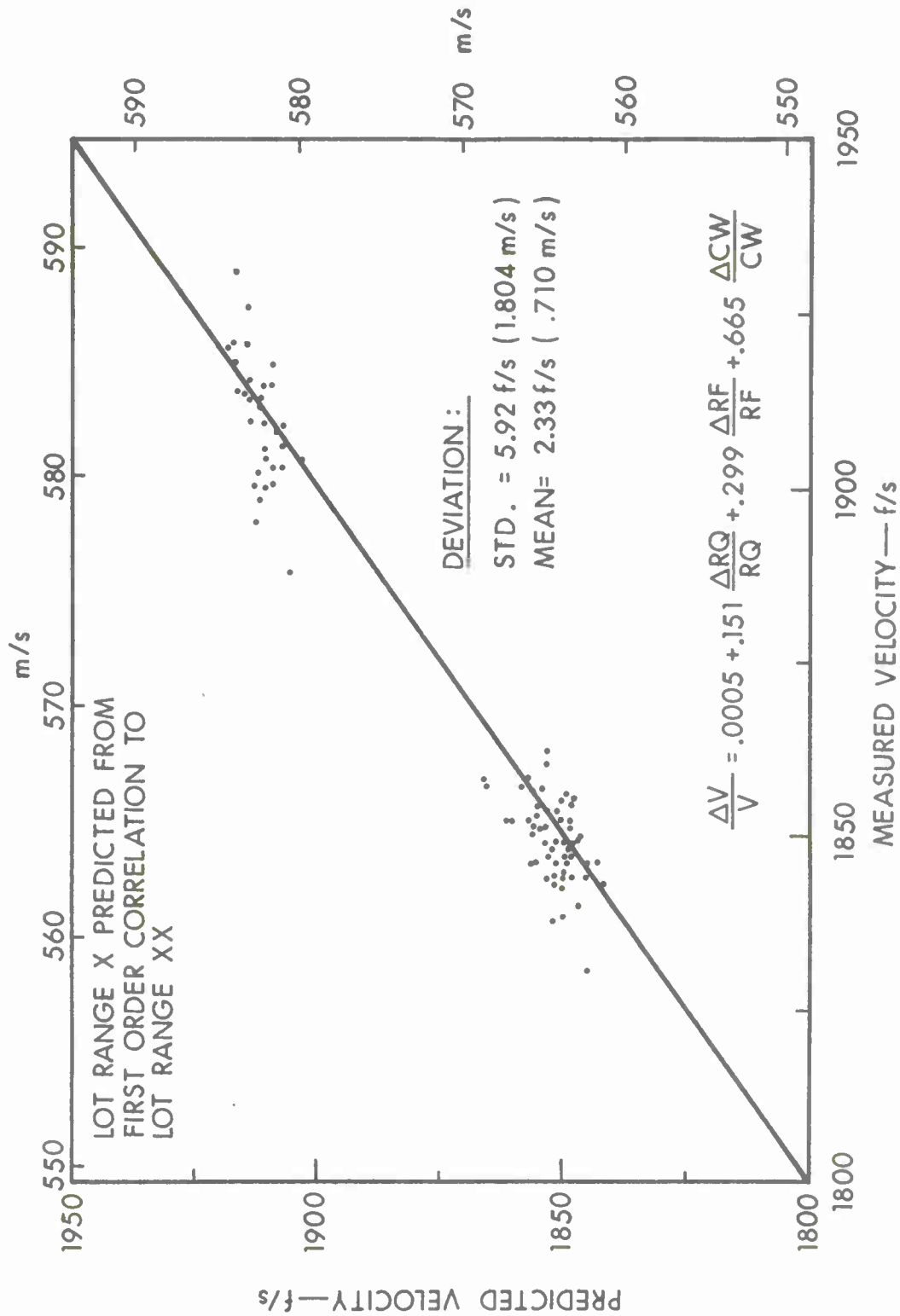


Fig. 9. Prediction of Muzzle Velocities for 155-mm Gun Propellant Lots Using Differential Coefficients Lot RangeX Predicted from First Order Correlation to Lot Range XX

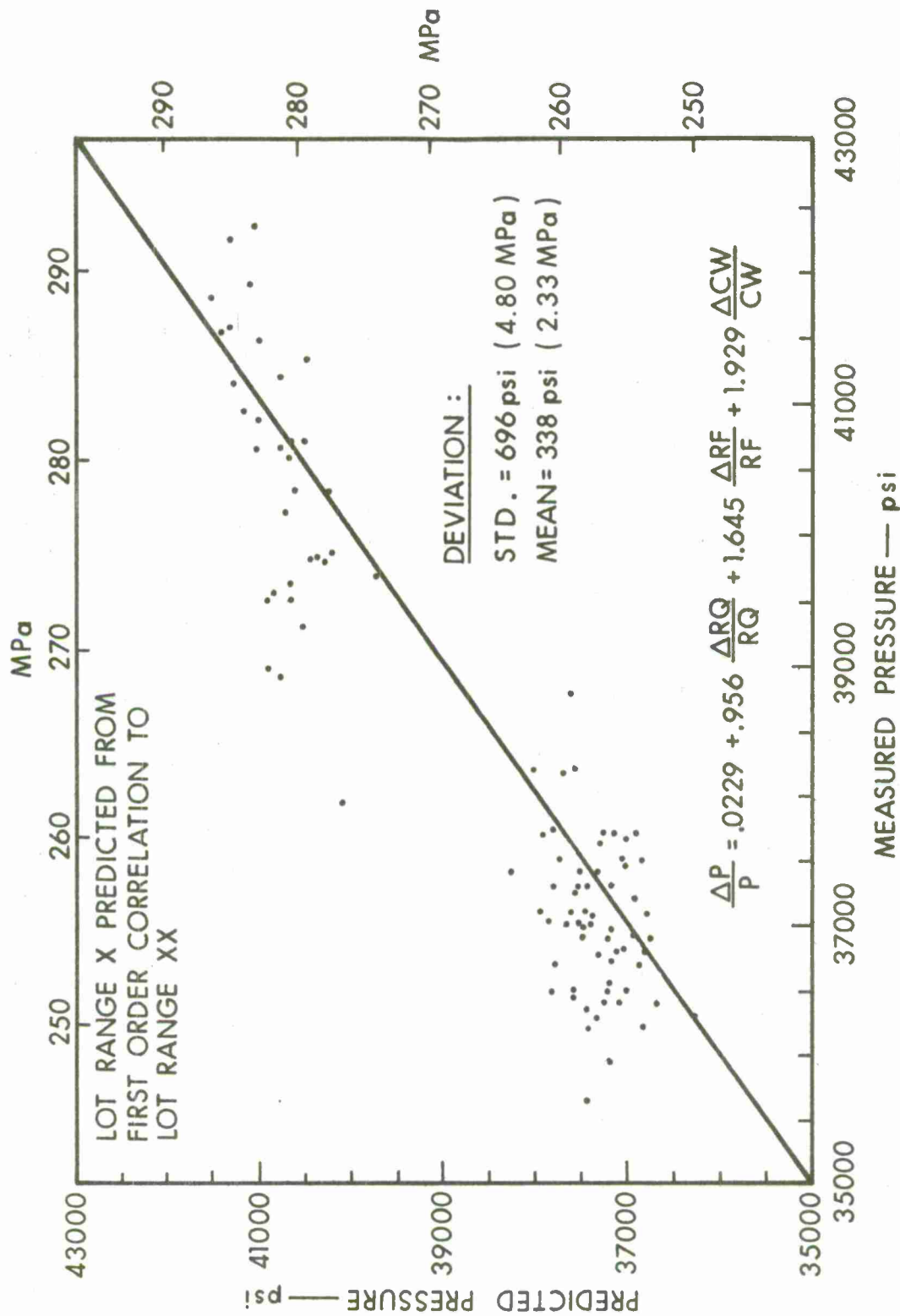


Fig. 10. Prediction of Maximum Breech Pressures for 155-mm Gun Propellant Lots Using Differential Coefficients. Lot Range X Predicted from First Order Correlation to Lot Range XX

In Table VI are listed propellant lot ranges in which the predictions were made, the gun, the parameter predicted (either muzzle velocity or maximum breech pressure), the four adjustable parameters in the Hitchcock code which were varied in this study, the average error, the standard deviation of the error, and three times the standard deviation of the error. The last three entries are expressed as percentages of the standard values. In this study, three production propellant lot ranges were predicted, Lot Ranges A and B for the 175-mm gun and Lot Range X for the 155-mm howitzer. The normal values for the four adjustable parameters as determined by previous simulations with the Hitchcock code¹² are given in the first line of Table VI. For the next six sets of runs, in each of which muzzle velocity and maximum breech pressure are predicted simultaneously, the relative force exponent was used at its nominal value of 0.1667 or zero. A zero value for the relative force exponent would imply that variations in relative force would have no effect on predicted results. Indeed slightly improved predicted results are obtained for some of the correlations shown in Table VI. Such spread in relative force approaches the accuracy of the closed bomb measurements.

Plots of the predicted muzzle velocities or maximum breech pressures vs. measured muzzle velocities or maximum breech pressures for 175-mm gun Lot Range B, using nominal values of the adjustable parameters except that the relative force exponent was zero, are illustrated in Figures 11 and 12.

SUMMARY OF RESULTS

All of the results using either the differential coefficient method or the ballistic similitude method to date for the 155-mm howitzer and 175-mm gun production and experimental lots are summarized in Table VII. The results are given in terms of standard deviation of differences between predicted and measured results and in terms of the 99-percent Confidence Interval, with both values expressed in terms of percentages of standard values. The numbers given for the standard deviation and 99-percent Confidence Interval are expressed as a range of values between a minimum and a maximum. Not all of the differential coefficient correlations summarized in Table VII were detailed in Table IV. It is possible to compute the recommended charge weights using the ballistic similitude method, but this has not yet been done. In general, the standard deviation of error values for muzzle velocity using the differential coefficient method is about one-half that of the ballistic similitude method. For maximum breech pressures, the ballistic similitude method gives standard deviation error values approximately three times those given by the differential coefficient method.

Table VI. Errors in Prediction of Muzzle Velocities and Maximum Breech Pressures for
155-mm Howitzer and 175-mm Gun Propellant Lots Using the Hitchcock Code

| Propellant Lot Range | Gun | Parameter | RQ Exponent (e_1) | RF Exponent (e_2) | Kq | Kr | Average Error % SV | Standard Deviation, σ % SV | 3σ % SV |
|-------------------------|--------|-----------|-----------------------------|-----------------------------|------|------|-----------------------|--------------------------------------|-------------------|
| B | 175-mm | MV | 1.4 | 0.1667 | 0.25 | 0.05 | -0.488 | 0.640 | 1.92 |
| B | 175-mm | P | 1.4 | 0.1667 | 0.25 | 0.05 | -2.140 | 4.270 | 12.81 |
| B | 175-mm | MV | 1.4 | 0.0 | 0.25 | 0.05 | -0.353 | 0.550 | 1.65 |
| B | 175-mm | P | 1.4 | 0.0 | 0.25 | 0.05 | -1.241 | 3.490 | 10.47 |
| A | 175-mm | MV | 1.4 | 0.1667 | 0.25 | 0.05 | 0.724 | 0.490 | 1.47 |
| A | 175-mm | P | 1.4 | 0.1667 | 0.25 | 0.05 | 2.47 | 3.15 | 9.45 |
| A | 175-mm | MV | 1.4 | 0.0 | 0.25 | 0.05 | 0.464 | 0.700 | 2.10 |
| A | 175-mm | P | 1.4 | 0.0 | 0.25 | 0.05 | 0.946 | 4.490 | 13.47 |
| X | 155-mm | MV | 1.4 | 0.1667 | 0.25 | 0.05 | 0.150 | 0.610 | 1.83 |
| X | 155-mm | P | 1.4 | 0.1667 | 0.25 | 0.05 | 3.82 | 3.37 | 10.11 |
| X | 155-mm | MV | 1.4 | 0.0 | 0.25 | 0.05 | 0.681 | 0.520 | 1.56 |
| X | 155-mm | P | 1.4 | 0.0 | 0.25 | 0.05 | 6.71 | 2.950 | 8.85 |

MV - Muzzle velocity
P - Maximum breech pressure
SV - Standard value

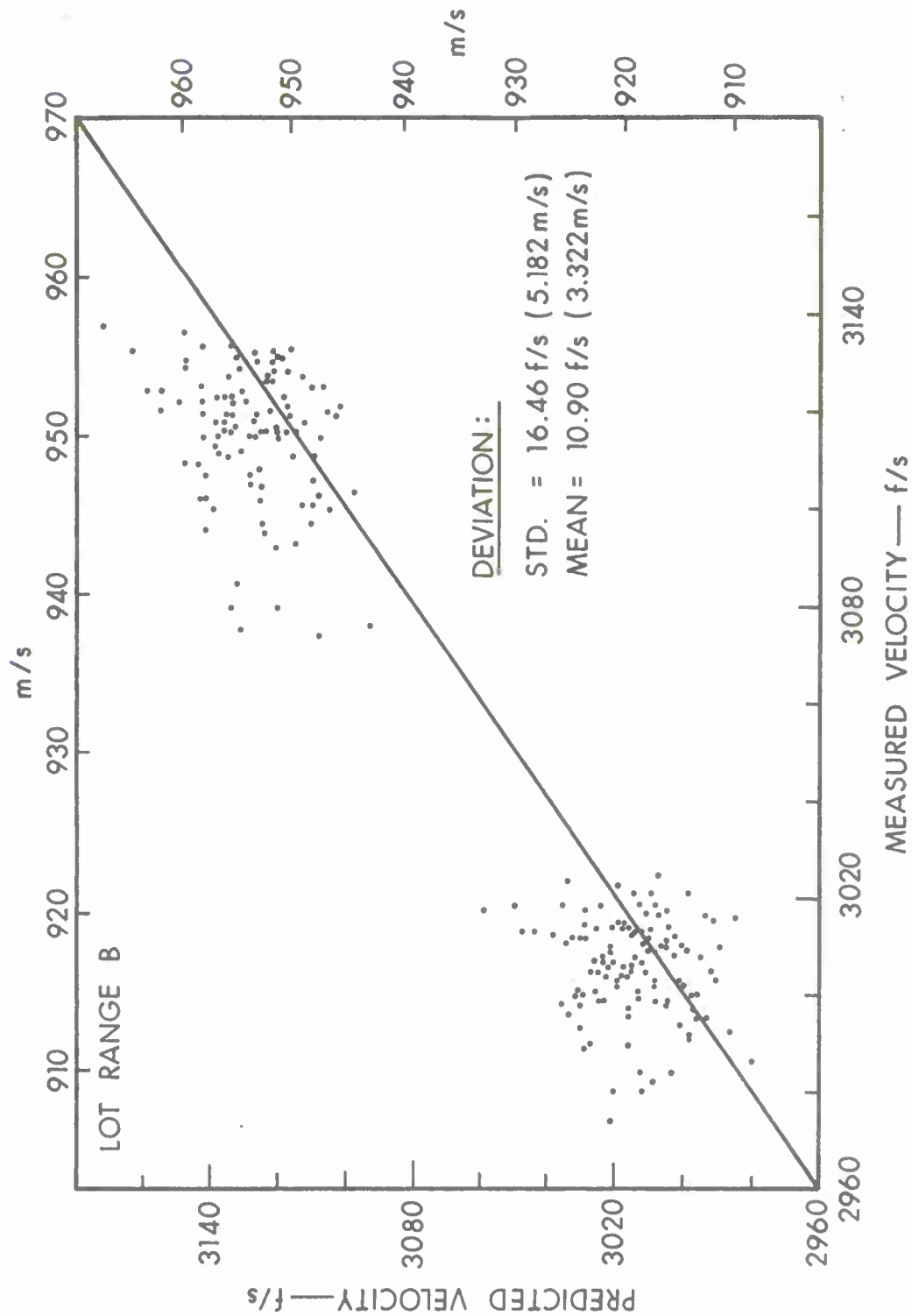


Fig. 11. Prediction of Muzzle Velocities for 175-mm Gun Propellant Lots (Lot Range B) Using the Hitchcock Code

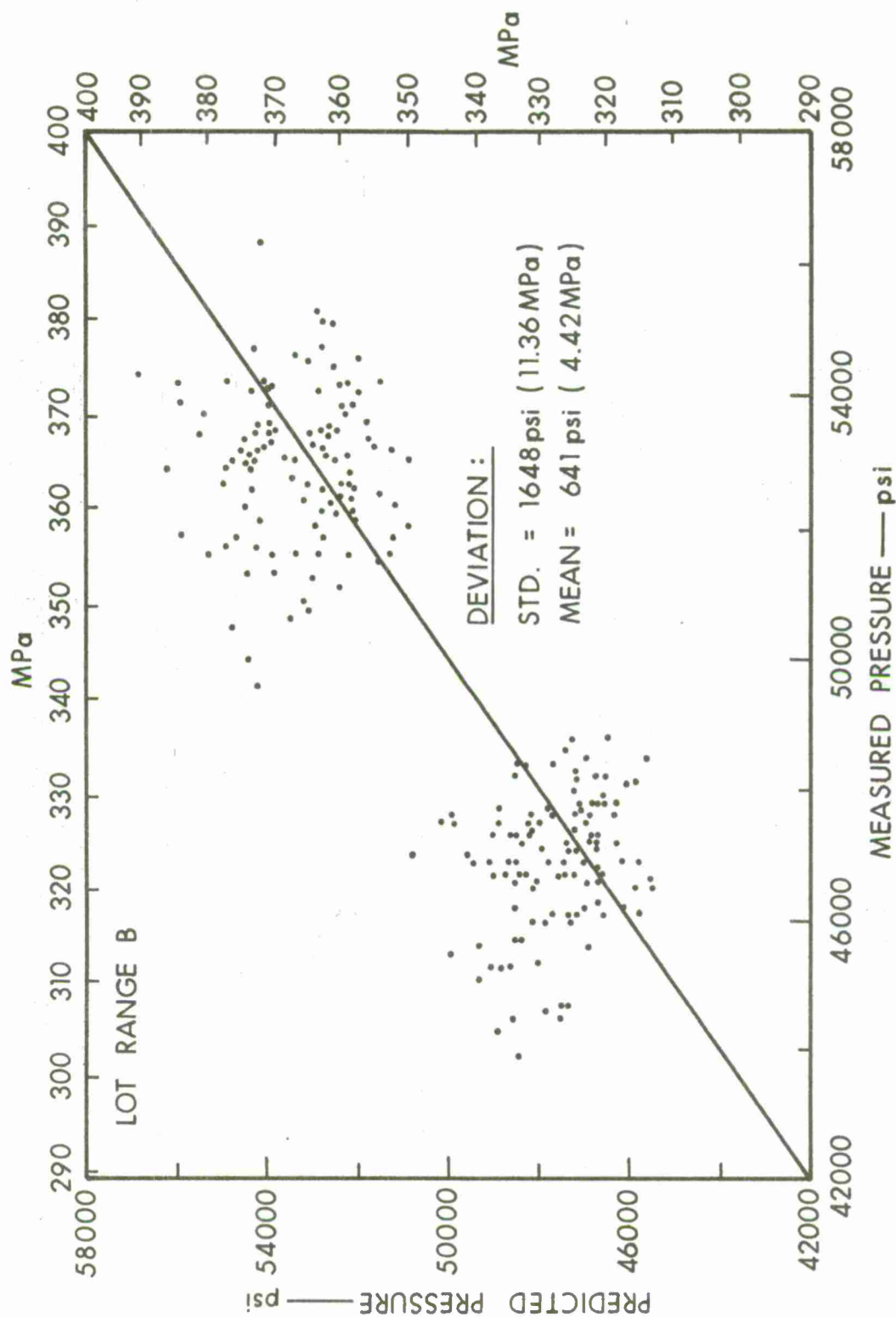


Fig. 12. Prediction of Maximum Breech Pressures for 175-mm Gun Propellant Lots (Lot Range B) Using the Hitchcock Code

Table VII. Summary of Results

| Gun | Model | Variable | Standard Deviation | 99% Confidence Interval |
|--------|-------|------------|--------------------|-------------------------|
| | | | % Standard Value | % Standard Value |
| 175-mm | DFC | Velocity | 0.23-0.58 | 0.69- 4.06 |
| 175-mm | DFC | Pressure | 0.70-4.21 | 4.64-29.46 |
| 175-mm | DFC | Rec Chg Wt | 0.44-0.65 | 1.23- 6.56 |
| 155-mm | DFC | Velocity | 0.18-1.11 | 0.67- 3.23 |
| 155-mm | DFC | Pressure | 0.94-9.40 | 3.58-27.50 |
| 155-mm | DFC | Rec Chg Wt | 0.41-0.46 | 1.09- 1.63 |
| 175-mm | H | Velocity | 0.49-0.73 | - |
| 175-mm | H | Pressure | 3.15-4.70 | - |
| 155-mm | H | Velocity | 0.51-0.61 | - |
| 155-mm | H | Pressure | 2.95-3.37 | - |

DFC - Differential Coefficient Method

H - Ballistic Similitude Method (Hitchcock Code)

Rec Chg Wt - Recommended Charge Weight

EFFECTS OF CLOSED CHAMBER MEASUREMENT ERRORS

An attempt was made to assess the effects that errors in closed chamber measurement would have on predicted muzzle velocity. Unpublished data¹³ from Radford Army Ammunition Plant gave closed chamber measurement errors for the 175-mm gun experimental propellant lots RAD-A-PEI-441-1 to RAD-H-PEI-441-1. These data are summarized in Table VIII for the particular data reduction techniques used in determining the relative quickness and relative force published in the propellant description sheets. The average values were used in the regression analysis for the differential coefficient method. The differential coefficient method used to predict muzzle velocities was a first order fit with constant term to Lot Range C (RAD A to RAD H). This equation is:

$$\frac{\Delta V}{V} = 0.0009 + 0.299 \frac{\Delta RQ}{RQ} + 0.539 \frac{\Delta RF}{RF} \quad (5)$$

Listed in Table VIII are the minimum, maximum, average, and standard deviation values for relative quickness and relative force. Also given are the predicted sample-to-sample standard deviations in muzzle velocities using the differential coefficient method. Six samples from each lot were fired in the closed chamber to give the values listed.

¹³

Letter, "Project AUTOCAP (RAAP Project PE-441)," Radford Army Ammunition Plant, 26 September 1974.

Table VIII. Effects of Closed Chamber Measurement Errors
on Predictions Using First Order Fit

175-mm Experimental Propellant Lots RAD A to RAD H
6 Closed Chamber Firings
IBM Filtered Reduction Technique

| Lot | RQ | | | | RF | | | | Vel SD | |
|-----|-------|-------|-------|------|-------|-------|-------|------|--------|-----|
| | Min | Max | Ave | SD | Min | Max | Ave | SD | f/s | m/s |
| A | 99.8 | 104.0 | 102.8 | 1.57 | 100.2 | 102.1 | 101.0 | 0.70 | 25.4 | 7.7 |
| B | 109.6 | 112.2 | 110.8 | 0.98 | 101.2 | 103.4 | 102.0 | 0.73 | 20.6 | 6.3 |
| C | 94.7 | 99.0 | 97.2 | 1.54 | 100.3 | 101.1 | 100.7 | 0.36 | 19.6 | 6.0 |
| D | 103.2 | 109.3 | 106.5 | 2.46 | 101.7 | 102.5 | 102.0 | 0.25 | 26.1 | 7.8 |
| E | 92.2 | 94.8 | 92.9 | 0.93 | 99.5 | 100.4 | 99.8 | 0.36 | 14.1 | 4.3 |
| F | 100.3 | 104.5 | 102.8 | 1.66 | 100.9 | 101.7 | 101.2 | 0.31 | 20.0 | 6.1 |
| G | 82.5 | 85.0 | 83.4 | 1.01 | 94.6 | 95.9 | 95.3 | 0.52 | 17.5 | 5.3 |
| H | 83.2 | 86.7 | 84.9 | 1.19 | 94.6 | 95.5 | 95.1 | 0.30 | 15.5 | 4.7 |

SD - Round-to-Round Standard Deviation

Note that the standard deviations in predicted muzzle velocity range from 14.1 f/s (4.3 m/s) to 26.1 f/s (7.8 m/s). This represents an 0.5- to 0.9-percent variation of the standard muzzle velocity. Since, according to Table I, the maximum round-to-round standard deviation is 0.33 percent of the standard muzzle velocity, it is apparent that these muzzle velocity standard deviations, if they had appeared in gun firings, would cause the lots to be rejected. Since such round-to-round standard deviations were not observed in the gun firings for these lots (round-to-round standard deviation in muzzle velocity ranged from 0.13 percent to 0.33 percent according to Reference 14), it is apparent that these closed chamber standard deviations are mainly measurement errors and do not reflect propellant property variations within each propellant lot. While these measurement errors will not cause round-to-round standard deviation errors in gun firings, they will seriously affect the ability of a model to properly predict the results of a gun firing.

CONCLUSIONS

From the results of this study, it can be concluded that the wholly empirical differential coefficient method will predict values of muzzle velocities and maximum breech pressures better than the ballistic similitude method. The drawback of the differential coefficient method is

¹⁴"Product Improvement Test of Charge Propelling, 175-mm, M86A2 (Evaluation of Propellant Variables on Ballistic Performance)," Firing Record No. P-82419, Aberdeen Proving Ground, Maryland, 1 April 1974.

that it will require experimental firing of a set of propellant lots whose ballistic properties will span the complete range of properties expected during production.

The ballistic similitude method can be used for start-up with a new propellant and/or a new gun since the method requires a minimum firing of one lot to calibrate the model. More research and better input data are needed in order to completely replace the differential coefficient method with the ballistic similitude method or other interior ballistic models of greater complexity.

Closed chamber measurement errors seriously affect the ability of the models to predict the ballistic performance of guns. Improvements in both precision and accuracy of closed bomb burning rate and impetus parameters are essential. Coupled with these improvements, burning rate parameters different from the conventional relative quickness (e.g. vivacity or linear burning rate) may yield more accurate predictions.

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